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ABSTRACT

In the teaching of archaeology at the university level there is often conflict between the engineer and the humanist when looking at archaeological evidence. Nowhere is this more clear than in considering the very old puzzle of how ancient Egyptian engineers transported and erected huge stone obelisks using only human labor. The humanist, whose views are presently more popular, tends to look at large numbers of people--possibly war prisoners or slaves--pulling on ropes. The engineer, considering the forces involved, dismisses this approach as totally impractical. The university instructor may well be in the middle. This paper, therefore, proposes a new interpretation of the continuing puzzle about the methods used by ancient Egyptian engineers to transport and erect large obelisks while using only humans as the source of power. It provides an engineering approach which is tied to the archaeological background of the subject matter. Specifically, it extends the work of R. Engelbach and emphasizes the 1168 ton unfinished obelisk at Aswan. The technique involves use of the "semi-hydraulic" properties of sand. This paper develops independent archaeological evidence which strongly indicates such knowledge was available and used for all of the known large obelisks. (Contains 31 footnotes and 11 tables, charts, and figures.) (Author/NB)

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A New Interpretation of the Transport and Erection of Large Obelisks by Ancient Egyptian Engineers

by
William J. Spry, Ph.D.

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A New Interpretation of the Transport and Erection of Large Obelisks by Ancient Egyptian Engineers or Engelbach Revisited

William J. Spry, Ph.D.

Summary

In the teaching of archaeology at the university level there is often conflict between the engineer and the humanist when looking at archaeological evidence. No where is this more clear than in considering the very old puzzle of how ancient Egyptian engineers transported and erected huge stone obelisks using only human labor. The humanist, whose views are presently more popular, tends to look at large numbers of people, possibly war prisoners or slaves, pulling on ropes. The engineer, considering the forces involved, dismisses this approach as totally impractical. The university instructor may well be in the middle.

This article therefore proposes a new interpretation of the continuing puzzle about methods used by ancient Egyptian engineers to transport and erect large obelisks while using only humans as the source of power. It provides an engineering approach which is tied to the archaeological background of the subject matter. Specifically it extends the work of R. Engelbach[1], and emphasizes the 1168 ton unfinished obelisk at Aswan. The technique involves use of the "semi-hydraulic" properties of sand. This article develops independent archaeological evidence which strongly indicates such knowledge was available and used for all of the known large obelisks.

Introduction:

The actual techniques employed by ancient Egyptian engineers to erect massive stone obelisks from their original horizontal position to a final vertical orientation have remained a puzzle since these immense objects were first seen by "modern" archaeologists[2]. A representative large obelisk of brittle granite would weigh more than 200 tons. Presently there is general agreement that the obelisk was first pulled up a ramp by humans using ropes. It was then rotated to a vertical position. A statement of modern thinking on the subject is expressed in a recent Smithsonian Magazine article[3]. The difficulty with this thought pattern is not with the Egyptian capability to assemble large groups of workers. Instead the problem is in understanding how the workers and ropes

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1 **The Problem of the Obelisks, by R. Engelbach; T. Fisher Unwin, Limited, London, 1923.**

2 A History of Science; Sarton, George; Harvard University Press, Cambridge 1952, pp30-35.

3 The Smithsonian Magazine, January 1997, pp.-26; "A Nova crew strains, and chants, to solve the obelisk mystery".

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were attached to the obelisk in a restricted space to effectively apply the large direct forces required to move the obelisk up a ramp prior to rotation to an erect orientation.

Performing reverse engineering on existing data, a dimensional analysis of ten large Egyptian obelisks provides strong evidence that ancient Egyptian engineers designed these massive stone structures to be transported and erected by using the "semi-hydraulic" properties of sand as a working tool. The use of sand as a "hydraulic ram" or "sand engine" to produce a large horizontal force effectively multiplied the effectiveness of the human work force involved. This analysis extends the classic work of R. Engelbach[4] on the subject with particular focus on the probable method for transport and erection contemplated for the unfinished obelisk at the Aswan quarries. Although unfinished due to a flaw in the granite, enough labor had been expended prior to discovery of the fatal flaw to make it certain that the ancient Egyptian engineers had a workable method in mind[5]. This 1168 ton obelisk is the largest known, and if problems concerning its transport and erection can be solved, the same methods will work for all other known Egyptian obelisks. Perhaps surprisingly, the direct use of sand as a working "hydraulic ram" or "sand engine" makes transport and erection possible for all of the large obelisks using only a relatively small, trained human work force; thus solving the major parts of the obelisk puzzle.

Difficulties with the "Pulling on Ropes" Theory

Engelbach considered the presently accepted "men pulling on ropes" theory directly and attempted to apply it to the 1168 ton unfinished Aswan obelisk. The number of men required for pulling quickly became astronomical. For the original removal of the obelisk from the valley of the quarry, Engelbach calculated that forty 7 1/4" palm strand ropes would be needed. These would need to be pulled by 6,000 men. To handle the Aswan obelisk on a "slight" slope on greased skids his calculation rises to 11,000 men "which is outside the bounds of possibility"[6]. Other archaeological evidence in support of the "men pulling on ropes" hypothesis for the main motive force is not positive from any direct engineering perspective. Again referencing Engelbach's work, the illustration showing the obelisk of Hatshepsowet on a sled with ropes attached needs much explanation. "The position of the hauling ropes ---- must also surely be wrong, as that would be the very worst position for pulling the obelisk, ---- It seems likely too that the obelisk was on the sled the reverse way round". With no hint of any other approach that would be valid in the archaeological time frame, Engelbach assumes these errors were because the drawing was "done by the court artist from memory etc."[7].. Another possibility of course has to be considered, i.e. that the main force for moving such an immense stone object was not a very large group of men pulling on ropes. It is certainly

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4 **ibid. footnote #1.**
5 **ibid. footnote #1, page 52.**
6 **ibid. footnote #1, page 56.**
7 **ibid. footnote #1, pp. 57-58.**

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clear, however, that the Egyptian engineers had some practical method in mind for the huge unfinished Aswan obelisk.

The Hint of a Different Approach

Unfortunately, until the discovery of vertical shaft tombs in Egypt (dating to approximately 500BC), there has been no good archaeological hint for suggesting any alternate approach. Only ropes and human chains seemed within the known limits of engineering knowledge in the earlier time period between 1400-1700BC when the large obelisks were cut from granite and erected. However, recent examinations of vertical shaft tombs such as that at Abusir[8] Egypt possibly do provide new hints regarding the continuing puzzle of the obelisks. In these vertical shaft tombs the "semi-hydraulic" properties of sand were used to lower the sarcophagi to their final resting place. Sand initially supported the tomb at the top of a main vertical shaft. Horizontal connecting passages at the bottom of the main shaft led to auxiliary vertical shafts that allowed this sand to be removed from the bottom of the main shaft in a controlled manner. As the sand was removed, the tomb sank slowly and evenly to its final resting place. The question becomes whether any separate evidence exists that indicates this type of knowledge about the properties of dry un-compacted sand was available approximately 1000 years earlier. More directly, is there any evidence that sand was piled against the base of large horizontal obelisks to produce a horizontal force that helped move them up a suitable ramp as part of the transport and erection method?

Development of the Evidence

In the first of three following sections the horizontal force of a pile of sand against a vertical surface is developed quantitatively in modern terms. This becomes the "sand engine". In the second, statistical design evidence, based on the measurements of ten existing obelisks, is developed to show that the Egyptian engineers constructed the large obelisks to be moved with the aid of sand. Part three then shows that a simple modeling process was available to the Egyptian engineers by which the obelisk designs could be tested before labor was expended to cut them in full size from the quarry granite.

The Use of a "Hydraulic Sand Ram" in Modern Terms

Since this entire approach involves the use of dry, un-compacted sand, a review of sand properties is in order. There are many types of sand or silty sand[9] throughout the world. For the purpose of this article the defining characteristic of a sand type is it's angle of repose or drained friction angle. This is the angle that a pile of sand forms naturally when piled on a flat surface. This angle defines the magnitude of the horizontal force such a sand type exerts when piled against a vertical surface. These angles typically range from

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8 **National Geographic, Nov. 1998, Vol. 194 No. 5, page 102 and following.**

9 **As used in this article "sand" is defined as a loose granular material resulting from the disintegration of rocks.**

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20 to 46 degrees[10] With the desert conditions surrounding the river Nile at the center of the Egyptian civilization there are readily available sands of almost every different type. In developing the hypothesis of an ancient "hydraulic sand ram" utilizing this horizontal force of a sand pile, it is only necessary to refer to the original work of Rankine[11] on the stability of loose earth aggregates such as sand. This is discussed in modern engineering texts on soil mechanics such as that by Das[12].

One fascinating point is that all of the "semi-hydraulic" properties of dry un-compacted sand that would make it suitable for an ancient "hydraulic sand ram" or "sand engine" are tied to this easily observable and easily measured angle of repose. The smaller the angle of repose, the greater the active horizontal force exerted by a pile of that type of sand against a vertical wall or the vertical base of a horizontal obelisk. Sand with "jagged" particles tends to remain at a steep angle. Sand worn to "rounded" particles by constant movement and grinding becomes more like a pile of marbles or ball bearings. These flow outward and transmit a larger active horizontal force when constrained by a vertical surface. The horizontal force of sand piled against a vertical surface is just the weight of the sand which is trying to slide downward until the natural angle of repose is established. This is the essence of Rankine's work. The Egyptian engineers could have looked at a pile of sand and visually judged, or easily measured, whether it would make a good candidate for use in a "hydraulic sand ram". The applicable general formula, first quantified by Rankine in 1857, is $\sigma_h / \sigma_v = \tan^2(45-\Ø/2)$. σ_h is the coefficient of active horizontal pressure in pounds per square foot. σ_v is the coefficient of vertical pressure in pounds per square foot (due to the weight of sand per cubic foot). Ø equals the drained friction angle (or angle of repose) for that sand[13].

For a mental comparison of the forces available from a pile of dry un-compacted sand, consider a concrete wall or dam across a stream of water that is filled to the top of the dam. In terms of Rankine's formula water is a "loose aggregate" with a drained friction angle of zero degrees. That is an initial "pile" of water will flow outward until it is flat and Ø = zero. $\tan^2(45-\Ø/2)$ becomes $\tan^2(45)$ and $\sigma_h = \sigma_v$. The active horizontal pressure of the water equals the vertical water pressure. Since fresh water weighs about 62 pounds per cubic foot, the horizontal pressure on the dam wall increases by 62 pounds per square foot for each one foot depth of the water contained by the dam.

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10 "Foundation Analysis and Design, 5th Edition", J. E. Bowles, Wiley & Sons 1969, p108, Table 2-6: or "An Introduction to Geotechnical Engineering", Holtz & Kovacs, Prentis Hall Inc. 1981, p.516, Table 11-2 or "Soil Mechanics", Lambe & Whitman, Wiley & Sons 1969, p149, Table 11.3.

11 Rankine, J. B. (1857), "On the Stability of Loose Earth," Philosophical Transactions of the Royal Society of London, Vol. 147, Part 1, pp. 9-27

12 Advanced Soil Mechanics, Second Edition, Braja M. Das, California State University, Sacramento.

13 ibid. footnote #12, pp. 385-388

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The total horizontal force on the dam wall can be calculated by integrating this horizontal pressure over the complete area of the dam wall.

Now assume the dam is filled instead with a level body of sand with an angle of repose (drained friction angle) equal to 30 degrees[14]. Rankine's standard formula $Tan^2(45-Ø/2)$ becomes $Tan^2(30)$ which has a value of precisely 1/3. Thus the active horizontal pressure of this sand is 1/3 the vertical pressure. As with water this horizontal force increases linearly with the depth of the sand behind the dam wall. Dry, un-compacted sand weighs approximately 100 lbs. per cubic foot. Thus at one foot of depth the active horizontal pressure of the sand will equal about 33 pounds per square foot, i.e. 1/3rd the vertical pressure at a depth of one foot, using the above estimate for density of sand. For two feet of depth the horizontal pressure becomes about 67 pounds and so on. Thus the active horizontal force of this sand against the dam wall is somewhat more than 1/2 the force which would occur if the dam were filled with water. Such large horizontal forces would have been very significant for the movement of large stone bodies such as obelisks.

Sand, for the ancient Egyptians, had one huge advantage over water as a "hydraulic" fluid. It doesn't need to be contained on it's back side. It can just be piled against a wall or the vertical base of a stone that needs to be moved.

To demonstrate the useful magnitude of this force for moving large obelisks, assume that sand with a 28 degree angle of repose is piled against the nearly vertical base of the horizontal unfinished Aswan obelisk. Table I[15] gives the dimensions of this base as 13.8 feet square. Assume that the sand is piled to the "top" of this base. The total horizontal force becomes approximately 47,431 pounds[16]. This is within 625 pounds of the force needed to overcome the downward force of gravity on a 2% grade, which is approximately 48,056 pounds[17]. The human work force now only needs to overcome

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[14] A reasonable angle for sand, and easily calculated using Rankine's formula.

[15] Table I is an extension of the Engelbach table, footnote #1, p30

[16] The horizontal force coefficient (Rankine) becomes $sigma_h = sigma_v \times (tan^2(45-Ø/2))$ where Ø = 28degrees. This result is approximately .36 times the vertical pressure of the sand column at a depth "x" feet from the top. The differential force at a depth of "x" feet equals the sand density (100lbs./cubic foot) times the width of the obelisk base (13.8 feet) times the horizontal force coefficient. This becomes approximately 100lbs./cubic foot x 13.8feet x .36. Integrating this differential horizontal force from a depth of zero at the "top" of the horizontal obelisk base to the "bottom" of the base (13.8 feet below) gives the total horizontal force against the obelisk base. The resultant integration gives (100lbs.per $ft.^3$)x(13.8ft. width)x.36x(the 13.8 foot depth of the sand pile in $feet)^2$x1/2 = 47,431 lbs.

[17] The minimum force needed equals the obelisk weight (1168 tons) x Sin(ArcTan(% grade=.02) or 48,056 lbs.

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slightly more then the forces of friction in the obelisk support system to move this immense obelisk up such a grade. Such a ramp grade would be constructed to properly elevate the horizontal obelisk before final rotation to an erect position. To put a 2% grade in perspective, it is near the maximum grade for a modern railroad.

Archaeological Evidence for the "Sand Engine" Hypothesis

At best the vertical shaft tombs of a much later date only hint at the earlier use of sand as a working "semi-hydraulic" tool by the Egyptians. The "hydraulic sand ram" hypothesis has to be validated with archaeological evidence existing at the time the obelisks were constructed. One investigative method meeting this condition is to examine the dimensions of existing large obelisks to determine if their individual designs were developed so that **a single type of sand** would be adequate to "push" each and every obelisk up its selected ramp to the desired elevation for final rotation to a vertical orientation. This sand could have been available near the Aswan quarry, for example. All obelisks come from the quarries of Aswan[18] This is a very limiting condition. The method must be statistical since the horizontal force developed by any sand piled against the vertical surface of any horizontal obelisk will push that obelisk up some slope. The test is applied to the range of obelisks listed in Table I as taken from the Engelbach text[19]. It shows the range of weights, tapers, and base dimensions of nine existing large obelisks plus the very large "unfinished Aswan obelisk"[20]. Weights in this test group vary over a range of 9.7 to 1, base dimensions vary by over 2.2 to 1, and shaft tapers vary by 1.8 to 1. Asterisks in the Table I denote obelisks whose dimensions "are scaled off photographs, making slight allowances for foreshortening"[21]. Names are assigned "after Gorringe, Egyptian Obelisks"[22].

For the mechanical purpose of this analysis each obelisk can be described by three independent variables: its weight, the dimension of its square base, and the taper of its sides[23]. The major constraint placed on the analysis is the assumption that all of the large obelisks were designed to be transported with the primary assistance, or "push", of **a**

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18 **ibid. footnote #1, p..32**

19 **ibid. footnote #1, p.30**

20 **Engelbach's table also lists an obelisk defined as "Later Aswan". It has not been used in the statistical analysis, although it alters the overall result very little. This obelisk is inferred from lines marked on granite in an attempt to find some use for a flawed section of quarry stone. Work had not proceeded nearly as far as on the 1168 ton "unfinished obelisk" of Engelbach's text and the final inferred shape is not as clear.**

21 **ibid. footnote #1, p.29**

22 **ibid. footnote #1, p. 30**

23 **These three variables form a complete set since each obelisk has the same general shape, a tapered square section from the base up with a pyramid at the top. Also each is cut from a single slab of granite, hence is completely uniform.**

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single type of sand. The complete analysis is repeated for two types of ramp slope. In the initial analysis each obelisk is assumed to be pushed up a ramp whose slope equals the taper of that obelisks' sides, i.e. the base of each obelisk is an "exact" vertical surface when it rests horizontally on the elevating ramp constructed for it. In the second case one common slope is assumed to have been planned and used for all the obelisks. The mathematical approach is the same for each choice of slope, that is to find if there is **a single optimum sand type** that gives a statistical best fit to the entire data set containing the measurements of all the existing large obelisks described by Engelbach.

A perfect fit to the hypothesis would find that the difference between the downward force of gravity on the elevation ramp and the upward "push" of that one type of sand against each obelisk's base would be zero for all the obelisks in the set. The calculations start with a sand type (i.e. an angle or repose or drained friction angle) of 36 degrees. The result is ten "difference" forces for the ten obelisks using that one type of sand. This forms one table of forces. Each difference force in that table is then squared. These ten squared values are then summed and the square root of the average of this sum is calculated. In summary, a Root Mean Square analysis of variation is obtained using all ten known large obelisks for that one sand type, i.e. with one angle of repose (36 degrees in this case).

This analysis is then repeated for thirteen sand types, starting with an angle or repose of 36 degrees and ending with an angle of repose of 24 degrees. If the Egyptians designed their large obelisks to use **one type of sand** as a main motive force, then this series of resultant RMS values will pass through a definite minimum tied to a best fit for the **actual type of sand** which the Egyptians used. If the Egyptians did not design these large obelisks to be "pushed" by a particular sand type then no unique minimum will occur.

Table I is a single complete calculation table in the test prepared for one type of sand (with an angle of repose of 28 degrees). Each line of the Table contains the following data: (1) Each obelisk is considered to be pushed up a ramp with a slope equal to the taper of it's shape (1/2 the total taper of Column 4 taken from the Engelbach text). With this ramp slope the base of that horizontal obelisk is a vertical surface. (2) The gravitational force attempting to slide each obelisk down it's associated ramp is calculated for each obelisk; Column 6. This is directly related to the obelisk's weight and the ramp slope. (3) Sand is assumed to be piled to the top of each obelisk's vertical base. (4) The horizontal force of the pile of sand against the vertical base of each obelisk is calculated for the single common sand angle of repose using the Rankine formula. This force of the sand attempts to push the obelisk up it's particular ramp against the force of gravity. Column 7 shows this force for each obelisk. This force is directly related to the density of dry un-compacted sand (uniformly assumed to equal 100 lbs. per cu. ft.) and to the dimensions of each obelisk's base. (5) The difference force between the "upward push" of the sand piled against the obelisk base and the downward force of gravity is listed in column 8. This difference is positive if the "push" of the sand is greater than the force of gravity and negative if it is less. (6) These differences are squared. At the bottom left of

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Table I is the square root of the mean square of the sum of these values for the ten obelisks using the single angle of repose (sand type) of this particular Table. (7) As mentioned earlier, these calculations were then repeated in different tables to cover angles of repose from 36 degrees to 24 degrees.

The entire system of tables described above was also repeated a second time assuming that a common ramp slope was used uniformly for all ten obelisks. Again these additional tables were each prepared for all sand types (angles or repose) from 36 to 24 degrees.

Chart I shows the major result, including the "unfinished obelisk" at Aswan. The red curve is the result for ramp slopes constructed equal to the taper built into each obelisk. The blue trace is the result for the best fit common ramp slope of 2%. The minimum is very definite in both cases for sand with an angle of repose of 28 degrees. A slightly smaller minimum value is obtained by assuming that each ramp slope was constructed so that the bases of each horizontal obelisk were "exact" vertical surfaces. As Table I indicates, the net added force required for the 1168 ton "unfinished" Aswan obelisk is reduced to 625 pounds. Using sand, a reasonably small group of workers with ropes "graspable" by human hands now could provide the added force and guidance needed to move this immense stone up it's ramp until it attained an elevation where it could be rotated to a vertical position. The RMS deviation for all ten obelisks is only 1065 pounds.

However, the data of Table I is not symmetric about a zero net force. Table II shows the same calculations repeated for just the nine finished obelisks listed by Engelbach[24]. Chart #2 graphs this result. The RMS variation is now reduced to 642 pounds and the table of difference forces is nearly symmetric. In fact the average of the nine force differences is only 160 pounds. ..Here again the best fit "common" slope does not produce as definite a force minimum as the assumption that each ramp was constructed so that the base of it's obelisk was "exactly" vertical when it was located on that slope.

These results, based on "reverse engineering", are evidence that the Egyptians designed obelisks to use sand as a "hydraulic ram", particularly for the very large "unfinished" Aswan project. Graph #3 compares the two results shown in Graphs #1 and #2. The unfinished Aswan obelisk is 2.6 times heavier than any of the other large obelisks in Engelbach's data. It clearly shifts the optimum angle of repose from 30 degrees to 28 degrees, as well as forcing an asymmetry in the force variations about zero pounds. One plausible explanation is that the Egyptians had designed previous obelisks for sand with an angle of repose of 30 degrees, and then planned to produce the immense "unfinished" Aswan obelisk on discovering a more fluid sand with an angle of repose of 28 degrees.

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24 **The "Unfinished Aswan" result is included in Table II, but not used in the RMS calculation.**

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This change in sand directly affects the maximum height and weight for which an obelisk can be designed with a sand "hydraulic ram" or "sand engine" as the main motive force.

In all cases "men pulling on ropes" are now needed only to guide each obelisk on its ramp and to overcome friction in the suspension system beneath the obelisk. The drawing of the Hatshepsowet obelisk, mentioned earlier, can now be considered a fairly accurate representation of ropes attached to guide the obelisk in motion. Furthermore the drawing now has the obelisk mounted on it's sled "in the correct direction".

A Practical Egyptian Method for Designing Obelisks

There is a direct method by which the Egyptian engineers could have developed these obelisk "designs" within the framework of their base of knowledge. Straight forward dimensional analysis of the equation relating the downward push of gravity on a ramp slope to the upward push of sand indicates that the Egyptian engineers could have directly predicted the final behavior of the finished obelisks with small models. This approach can be demonstrated by applying it to a one tenth scale model of the 1168 ton unfinished Aswan obelisk. Such a model would have a base 1.38' square and be 13.7' high. It would weigh 1.168 tons and the difference force when placed on it's designed ramp would be less than one pound when sand with a 28 degree angle of repose is piled against its base.[25] Table III[26] column 4 shows one design parameter that stands out in three of the listed obelisks. The height of the "pyramadion's" for the unfinished Aswan, the later Aswan, and the Lateran obelisks are much greater than for the other eight. This removes weight effectively from the finished obelisk without reducing the overall height. It is also the easiest part to change on a scale model during the design process. With this modification these obelisks fit the general pattern, and probably indicate initial Egyptian efforts with 28 degree sand.

Moving Obelisks on the Elevating Ramps

Engelbach has reasoned with care that these large obelisks were first mounted on timber sleds and then moved on rollers[27]. The fragility of the immense unfinished Aswan obelisk makes the use of both sled and rollers mandatory. Otherwise any unevenness in the roadway or planking would have introduced local stresses beyond the tensile strength of the granite and led to disastrous cracking. Figure #1 is a diagrammatic sketch of the Aswan obelisk on a 2% ramp such that it's base is a vertical plane. Sand is shown piled against the base as a "sand engine" and is constrained in place by side walls (or a sand magazine), on the assumption that the Egyptians would not want to move more sand than necessary. Clearly these sides could be made in sections and move with the obelisk up the ramp. Following the reasoning of Engelbach, any ropes would be attached to the sled

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25 **To calculate this result directly using volumes, Engelbach's table (ibid. #1, p.30) gives the pyramidion height as 14..8' with a base of 8.2'.**

26 **ibid. footnote #2, p.30**

27 **ibid. footnote #2, pp. 56-60**

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rather than as shown in the artists rendition of the Hatshepsowet obelisk[28] which is taken from the sculptures at Der El-bahari.

To reduce friction it is assumed that the Egyptian engineers did cover the ramp surface with wooden planking and supported the obelisk on transverse wooden rollers. A bas relief at Deir-el-Bahari[29] shows an obelisk in a planked barge supported on transverse rollers. This is evidence that the engineers were aware of the advantages of both rollers and planking to reduce the effects of friction in moving large stone masses. It is unlikely that they would have discarded these methods after leaving the transport barge and moving the obelisk up an earthen ramp. This method could not easily have been used, however, if the obelisk were pulled directly up the ramp using ropes and large numbers of humans for the force required. Control of orientation would have been difficult and the obelisk would have had to be continually blocked to prevent it from disastrously rolling back down the ramp if a rope broke, or the work force temporarily stopped pulling. Neither of these events is a problem if the obelisk is continually moved and blocked by the "hydraulic sand ram", as shown in Figure #1.

The retaining walls on each side of the obelisk do not represent any particular problem. They could have been constructed using the relatively short pieces of lumber known to have been available to the Egyptians. The two walls could have been tied together by cross timbers placed underneath the planked roadway in advance and by cross timbers joining the tops of the two walls. This could readily be made strong enough using techniques the Egyptians employed for constructing water craft on the Nile. Since the Egyptians knew how to plank boats for use on water, they also certainly could plank the walls of a sand container in a leak proof manner.

What is needed for "primary power" when using sand is a relatively small number of humans acting as a conveyor belt; picking up containers of sand from the bottom rear of the pile shown in Figure #1, and dumping the sand on the top surface just behind the obelisk's base. A representative number might be fifteen workers in a single "conveyor" crew. The thirteen foot width of the Aswan obelisk base gives ample room for the line of workers. Each worker passes his container of sand to the next worker further up the sand slope. As an estimate, assume that each worker on the ramp can lift five twenty pound containers of sand one foot higher during each minute of work time. This rate could probably have been sustained over a twelve hour work day. When work stops, the obelisk would not need special blocking to prevent it from rolling back down the hill. The "hydraulic sand ram" holds it in place.

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28 **ibid. footnote #2, p.57**

29 **Fig. 51, p. 158, A History of Technology and Invention, Progress through the ages; The origin of Technical Civilization, Dumas Maurice, Translated Eileen Hennessy**

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Using these estimates the obelisk would move up the ramp at a rate determined by adding one cubic foot of sand per minute from a single human "conveyor belt". Five "twenty" pound containers per minute would be passed to the uppermost worker in the conveyor belt and dumped on the top surface of the sand pile. This is equal to 100 pounds per minute, or one cubic foot of sand per minute. The resultant rate of obelisk movement due to this addition of sand would be 3.8 feet per twelve hour day per "conveyor belt". With two shifts of men working steadily over twenty four hours (each shift forming a single fifteen man conveyor belt) the obelisk would move up the ramp at about the rate of 7.7 feet per day. Two lines of workers would move the obelisk about 15 feet per day; four lines would move it about 30 feet per day. This number of "human conveyor belts" would just about fill the available work space. This scenario has the advantage that the obelisk is never allowed to stop long enough to partially flatten the supporting rollers, which would have increased the effective friction. It would also be "slow" enough for the engineers to carefully place new rollers ahead of the obelisk to control its orientation as it moved. Possibly the biggest problem would have been moisture added to the sand. This problem would be quickly obvious, as the obelisk would stop moving. The generally dry climate of Egypt would minimize this possibility.

The problem of sand leakage through the side walls has been discussed earlier. The two vertical "cracks" between the vertical sides of the obelisk base and the wooden container walls requires separate mention. This gap would leak and present added friction to obelisk motion. It would leak, however, only until the 28 degree angle of stability is attained, and may have been neglected. However, the Egyptians knew how to make cloth. A simple cloth "gasket" attached to the obelisk base and sliding along the vertical side walls of the sand container could have controlled the leakage, and may have been used since it would increase the efficiency of the system.

Additional workers pulling on ropes could have provided the necessary force to overcome any remaining negative force due to gravity and to overcome friction in the rollers. Their numbers and the size of the needed ropes are now all within reason. However, Engelbach's reasoning, and direct evidence, indicate the use of sleds beneath the obelisk. This increases the depth of the sand, and the total horizontal force of a pile of sand against a vertical surface increases as the square of the depth of the sand. Using a wooden sled with a planked back surface that is built of timber 2' square, the force against the base of the unfinished Aswan obelisk increases from 47431 lbs. to 62175 lbs., leaving 14744 lbs. to overcome friction. No ropes would have been needed.

Rotation to the Final Erect Position

Once the horizontal obelisk is moved up the elevating ramp, the final engineering problem is to rotate it precisely to a vertical orientation, so that it fits in a turning groove[30] cut in the foundation stone on which the obelisk base finally rests. Engelbach,

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30 **See discussion in the Smithsonian Magazine Article referenced in footnote #3**

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tied to the pulling on ropes theory, considers that the obelisk was "let down (slid) "down a funnel shaped pit"[31] filled with sand until one side of the base slides into the turning groove. This assumes that ropes were used to pull the obelisk up the ramp with the base going first. There are at least two major problems with this approach that were recognized by Engelbach. First, the obelisk is not visible while being slid down its chute. Second, there is no clear way to remove the sled used to transport the obelisk. There is also no way to carve the final side of the obelisk without erecting extensive scaffolding after the obelisk is erected.

In this area there is no direct archaeological evidence to support any particular theory about the rotation process, but the problem becomes much simpler and the method more precise from a basic engineering viewpoint if the artist's rendition of the Hatshepsowet obelisk is taken seriously. In this rendition the top of the obelisk is in front, fitting the evidence that the horizontal obelisk was "pushed" up the ramp by sand piled against its base. Figure #1 is a representative sketch of an obelisk in this position.

Once the obelisk is "pushed" to the top of the ramp the basic physics problem is to make use of the gravitational potential energy of the raised horizontal obelisk, and of the piled sand beneath it, to cause the desired rotation, gently and controllably. This is accomplished by removing sand beneath the obelisk under controlled conditions. That is probably most easily done by using side containing walls in which open horizontal holes or "chutes" of specific dimensions are placed at desired locations. These "horizontal chutes" become "sand valves" identical to the concept employed much later in Egyptian vertical shaft tombs. Based on evidence for the use of sand to push a horizontal obelisk it is not unreasonable to assume that the Egyptians also used simple horizontal "sand valves" to lower and rotate the obelisk to its final vertical position. Engelbach makes an essentially similar assumption in his sketches and models.

Figure #2 shows a general example of a vertical stone wall with a rectangular hole forming a horizontal chute or "sand valve". As long as the horizontal section of the chute is more than two (or for example 1/tan(39 degrees)) times the vertical height of the opening, no sand will escape. Dry sand only flows until the angle of repose is established in the chute. A worker with a hoe on the outside of the wall removes sand from the "outside" of the chute at a controlled rate. In turn sand from the "inside" of the wall flows in the chute until the angle of repose is re-established. In this process the obelisk is gently lowered.

Figure #3 is a cross section side view of a completed ramp as it would appear with the obelisk in its final elevated, but horizontal position. The first of three walls needed in this approach is a slanted crib of stone, shown as "Wall A". It is a guide wall placed at an angle such that the obelisk would rest in a final intermediate, stable, but still somewhat tilted position when rotated and moved down against this wall. In this last intermediate position, one side of the obelisk bottom is in the "turning groove" of the obelisk's

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31 **Ibid. #1, p.69**

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foundation stone. This slanted "crib" wall would have to consist of substantial stones placed in position while the ramp was under construction, since sand will be removed from one side of it during the descent and rotation of the obelisk. The angle would be chosen so that the center of gravity of the obelisk would be just to the right of the turning groove, as sketched in Figure #3. This angle, easily calculated today, could have been determined directly by the original engineers by modeling the obelisk in a small size from a uniform material.

A "straight" but slanted shape is not a necessary, nor perhaps even desirable configuration for this guide wall "A". Also the "top" of the horizontal obelisk could be to the right (in the sketch) of the intersection with the guide wall. The wall (and associated ramp) as shown in Figure #3 requires that the ramp be considerably higher than other possible guide wall shapes. It also means that the internal "shear" angle of sand must be utilized to produce the necessary horizontal motion of the obelisk's center of gravity in order to get the base properly in the "turning groove". Finally the rotation with such a wall is centered about the upper end of the obelisk. This does minimizes undesirable mechanical tension in the obelisk shaft that might lead to cracking. Such a consideration would have been extremely important for the 1168 ton unfinished Aswan obelisk. The geometry is chosen here, however, only to demonstrate the complete control a small work force would have to precisely rotate and locate the obelisk in a vertical position.

For a ramp of minimum height the obelisk center of gravity (while still horizontal) needs to be placed just to the right (in the sketch) of a vertical from the turning groove. Moving the obelisk center of gravity horizontally during rotation is then minimized. Horizontal motion simply requires using more of the gravitational energy stored in the sand beneath the obelisk. If this revised position is used the ramp need be only slightly higher than the vertical distance of the obelisk's center of gravity above its "bottom" divided by the cosine of the internal angle of shear for "hydraulic" sand. As used throughout this article this internal angle of shear is assumed to be 45 degrees.. Rotation at this minimum ramp height, however, would maximize breaking stresses on the obelisk shaft (one half of its mass is completely unsupported). In order to minimize the total work effort for the project. some intermediate approach would almost certainly have been applied. It should be noted that the concept of a mathematical "center of gravity" had not been developed when the obelisks were originally erected. However, the "balance point" of the obelisk could readily have been determined from a small model constructed of uniform material. In like manner the internal angle of shear for the sand could have been determined by modeling the full scale operation.

Figure #4 shows a sketch of how side "control" walls could be placed properly in the ramp during the ramp's construction. These (marked "Wall B and "Wall C") are essential in this approach. They are constructed with a "lattice" of open horizontal chutes or "sand valves" at appropriate positions. While not archaeologically "proven" they can be understood in direct analogy to the Abusir vertical shaft tomb. These side walls do not need to be particularly robust as they (and the ramp to the left of the obelisk as drawn in Figure #3) would be progressively removed during the obelisk's descent and rotation; thus

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keeping the obelisk visible and its position accurately measurable and controllable. They could be made of any quarried stones placed in overlapping horizontal layers with an appropriate lattice of gaps at selected locations. While the stones have to be twice as wide as they are high, the horizontal length of the stones could be arbitrary as available. Sand therefore could be removed in a controlled fashion by a continued "hoeing" of selected chutes by the same relatively small, trained work force.

The Rotation Process

Although it has been suggested that simple removal of sand beneath the obelisk could be used to "tilt" it to its final position[32], further controls would be necessary to accomplish this rotation with precision that ensured the integrity of this brittle granite object. An obvious first point is that it would have been essential that the material directly beneath the obelisk consist of just fine "hydraulic sand", free of rocks and other extraneous matter. This area of selected sand is indicated in Figure #3. A second point is that the flow properties of sand would require its controlled removal in various stages to effect a complete rotation of the obelisk to a near vertical orientation using gravitational forces alone.

As an example, and just for this discussion, the elevated horizontal obelisk is positioned with its top just above the upper edge of the slanted "crib" (Wall "A" of Figure #3). With an initial assumption that the working internal "shear" angle of the sand is 45 degrees (it must be greater than the angle of repose of about 30 degrees), the 137 foot unfinished Aswan obelisk must be raised to an elevation of approximately 194 feet (137 feet divided by the cosine of 45 degrees).

If given enough time, the ramp could have been constructed by the same relatively small work force postulated earlier. Its construction is not essential to the argument, however, and it also could have been built separately by a larger work group. Ramp construction could well account for the large numbers of men assembled for these projects. Which ever was done, the approach proposed here assumes that all operations on the valuable obelisk were accomplished by a relatively small, trained work group. The base on which the obelisk finally rests would need to be located with precision at the outset, and the ramp constructed over it. The final location of the horizontal obelisk on the ramp would need to be accurate as well. To do this the Egyptian engineers would have been able to rely on their well recognized knowledge of "surveying".

Actual rotation and lowering the obelisk would proceed in several stages. At the start the angle between the base of the obelisk and the horizontal would be almost exactly ninety degrees. Initially sand could be removed from directly beneath the obelisk so that the obelisk would rotate about its "top". This would continue to an intermediate position with the angle between the obelisk's bottom and the horizontal steadily diminishing as rotation occurred. At some point rotation would stop. At this point the compacting of

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32 ibid. footnote #3

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the sand due to the gravitational component of the obelisk's weight perpendicular to its "bottom" would bring the system into a steady state. This angle would be somewhat greater than the "un-compacted" angle of repose. If sand were then removed from the zone defined by (1) the "inner" vertical surface of the obelisk, (2) a line traversing the base of the obelisk, and (3) the "tilted" crib " (Wall A) behind" the obelisk, the obelisk would remain stationary, and removal would cause this sand to be cleared from this triangular zone. This zone is indicated by the triangle defined by the letters "a", "b" and "c" in Figure #5.

Removing sand from the zone defined by the triangle "abc" would be a definite asset of this approach. The sled used to support the obelisk during transport could now be removed with care and precision. A further benefit is also clear. Three sides of the obelisk could have been carved and polished while it was horizontal and in transit to the final site. The fourth or "bottom" side would have been inaccessible. However, while in this intermediate stable position stone masons could finish the fourth side while standing on the top surface of the sand during its controlled removal. This surface is indicated by the line "d-e" of Figure #5.

With sand removed completely from the triangle "abc", the obelisk still remains stable. Assuming the effective internal shear (or slippage) angle for the sand is about 45 degrees, sand removed from the triangular area "bce" would cause the obelisk base to "slip" toward the slanted retaining wall. In this stage, sand is slipping beneath the obelisk base and the center of gravity of the sand beneath the obelisk is sliding to the right (in the sketch drawn as Fig. #3). Assuming an initial location of the obelisk with respect to wall "A", this horizontal motion of the obelisk's center of gravity is essential to bring one side of the obelisk into contact with the guide wall "A". As this procedure continued, the top sand slope would always remain at about thirty degrees to the horizontal. When the obelisk reached wall "A", sand would then be removed from beneath it until the obelisk descended into the turning groove. At that point remaining sand could be cleared from the base and the obelisk wedged or pulled into its final vertical position by the same relatively small work force.

Transport of the Obelisks from Shore to Nile Barge

Evidence showing the use of sand as a hydraulic tool also explains an accompanying and annoying problem of how the Egyptian moved these huge stones from shore to the deck of a barge in order to float them down the Nile from the Aswan quarry to their final destination. This is particularly true in the case of the 1168 ton Aswan obelisk. Egyptian cargo barges were brilliantly constructed from fairly short timbers held together by a fore and aft triangulated rope and beam support structure. They were inherently "weak" although a modern barge of steel would need to be treated with care during this loading process. The problem is to keep the floating barge vertically immobile, as well as horizontally immobile, while the obelisk is being loaded; and again when it is unloaded at its destination.

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Only one modification to the "sand engine" concept would have been needed. Sand has a similar though smaller density than granite. The barge would have needed a "sand magazine" constructed before hand on the same surface which would eventually contain the horizontal obelisk. Adding more sand than the weight of the obelisk, the barge could first be tested for floating stability, since the center of gravity of the sand loaded on the barge would be higher than when the barge was loaded by the expensive granite obelisk. Waterline reference marks would be placed on the hull and the square ended barge moored by ropes until it was horizontally immobile with one end toward the shore. A short planked ramp could connect the barge to shore and a "sand engine" similar to that in Figure #1 used to push the obelisk on the barge with a small human conveyor belt to move the sand. As the obelisk weight entered the barge, the water line marks would disappear. A second human conveyor belt would remove sand ahead of the obelisk such that the waterline marks would just remain visible. Thus the barge would remain vertically and horizontally immobile until the obelisk was loaded. At the final destination the process is reversed with the other end of the barge butted against the bank. Sand is added to the barge as the obelisk is removed, again keeping the barge vertically and horizontally immobile. In amusing contrast, and along with other problems, the use of ropes with human labor to pull the obelisk onto the barge seems to require that the work force was able to walk on water since pulleys had not yet been invented.

It should be noted that filling the barge with a pre-determined amount of water, and then pumping it out as the obelisk was loaded would not work. The "ballast" has to remain in place during the loading process or the barge tips. Sand will do this properly, but water ballast will not. Even a compartmented barge with a selection of water tight compartments would be a poor substitute. Also, use of sand as described above conforms to the known strengths and weaknesses in the construction of these ancient barges.

Conclusion

Postulating the general approach of a "sand engine" and "sand valves" is not unreasonable for the obelisk transport and erection process from the viewpoint of modern engineering knowledge. It provides a comprehensive solution to the "obelisk puzzle" that can be accomplished precisely by using only human labor. Further, there is strong evidence that the ancient Egyptian engineers had more knowledge of the "semi hydraulic" properties of sand then has been assumed and that they actually designed the obelisk shapes to make use of sand as the primary motive force for both their transport and their erection. Finally, this approach is surely as reasonable as the assumption that large numbers of workers were managed, organized and pulling in unison in a very restricted area to do the job.

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Table I
Sand Angle of Repose = 28 Degrees

Obelisk	Base Dimension (feet)	Total Height (feet)	Total Taper (See Text)	Weight (tons)	Required Force ForTaper (lbs.)	Horizontal Sand Force (lbs.)	Difference Force (lbs.)
Aswan	13.8	137.0	24.3	1168	48056	47431	-625
Lateran*	9.8	105.6	29.3	455	15527	16988	1461
Hatshepsowet	7.9	97.0	42.8	323	7546	8900	1353
Vatican	8.8	83.0	26.9	331	12303	12300	-3
Luxor*	8.2	28.2	28.2	254	9006	9952	946
Paris	8.0	74.0	26.5	227	8565	9241	676
New York*	7.7	69.6	29.0	193	6654	8240	1586
London*	7.8	68.5	27.4	187	6824	8565	1741
Mataria*	6.2	67.0	27.5	121	4399	4302	-98
Tuthmosis	7.0	64.0	24.2	143	5908	6190	283

RMS Deviation Including "unfinished" Aswan (lbs.) = 1065
Angle of Repose (degrees) = 28

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Table II
Sand Angle of Repose = 30 Degrees

Obelisk	Base Dimension (feet)	Total Height (feet)	Total Taper (See Text)	Weight (tons)	Required Force ForTaper (lbs.)	Horizontal Sand Force (lbs.)	Difference Force (lbs.)
Aswan	13.8	137.0	24.3	1168	48056	43792	-4264
Lateran*	9.8	105.6	29.3	455	15527	15684	158
Hatshepsowet	7.9	97.0	42.8	323	7546	8217	671
Vatican	8.8	83.0	26.9	331	12303	11356	-947
Luxor*	8.2	28.2	28.2	254	9006	9188	182
Paris	8.0	74.0	26.5	227	8565	8532	-33
New York*	7.7	69.6	29.0	193	6654	7608	954
London*	7.8	68.5	27.4	187	6824	7908	1084
Mataria*	6.2	67.0	27.5	121	4399	3971	-428
Tuthmosis	7.0	64.0	24.2	143	5908	5715	-192

RMS Deviation Minus "unfinished" Aswan Obelisks (lbs.) = 642
Angle of Repose (degrees) = 30

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Table III
Reference Table from Engelbach's Text p.30

Obelisk	Base Dimension (feet)	Pyramidon Base ft.	Pyramidon Height ft.	Total Height (feet)	Total Taper	Weight (tons)
Aswan	13.8	8.2	14.8	137.0	24.3	1168
Later Aswan	10.3	6.6	17.4	105	23.7	507
Lateran*	9.8	6.2	14.8	105.6	29.3	455
Hatshepsowet	7.9	5.8	9.7	97.0	42.8	323
Vatican	8.8	5.9	4.4	83.0	26.9	331
Luxor*	8.2	5.1	6.4	28.2	28.2	254
Paris	8.0	5.1	6.4	74.0	26.5	227
New York*	7.7	5.3	5.4	69.6	29.0	193
London*	7.8	5.3	5.4	68.5	27.4	187
Mataria*	6.2	4.0	6.6	67.0	27.5	121
Tuthmosis	7.0	4.6	7.8	64.0	24.2	143

1. *After Gorringe, Egyptian Obelisks*
2 By taper I mean the length of the shaft in which one unit decrease in width is observed.

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Chart #1 All Examined Obelisks

Design Tapers vs. Best Fit Common Taper

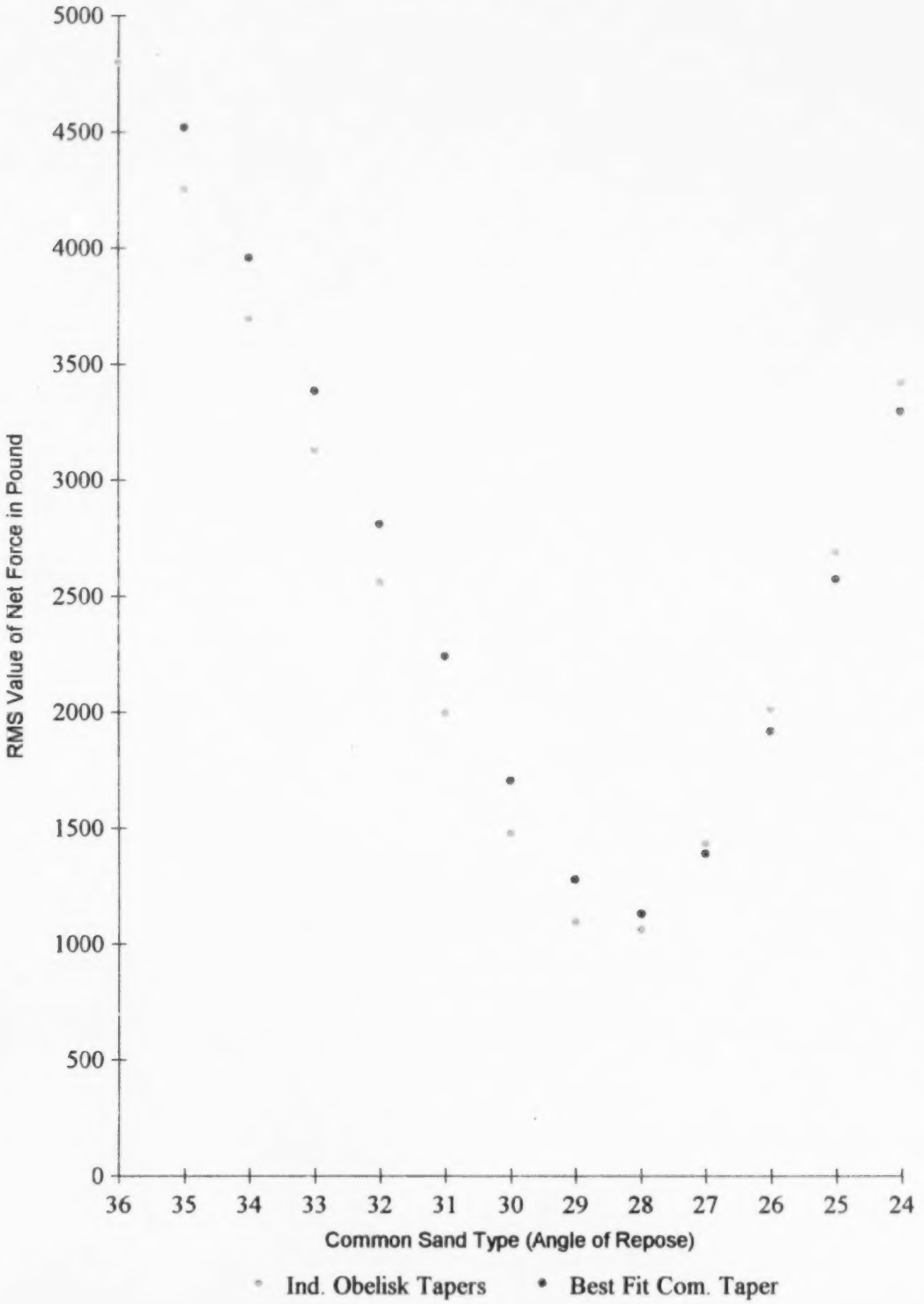

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Chart #2, All Completed Obelisks

Design Tapers vs. Best Fit Common Taper

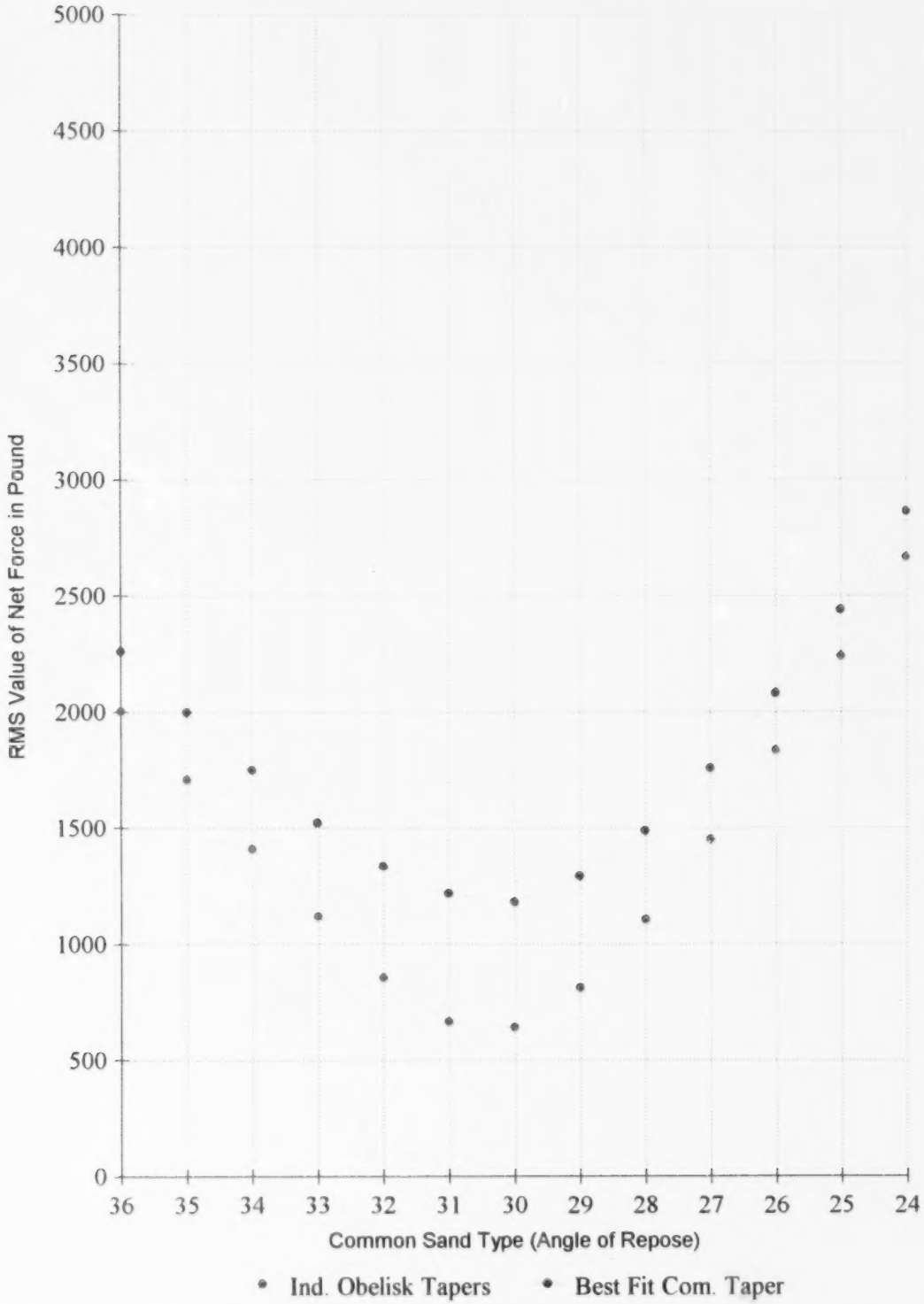

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Chart #3, Data Comparison

All Data vs. Finished Obelisks

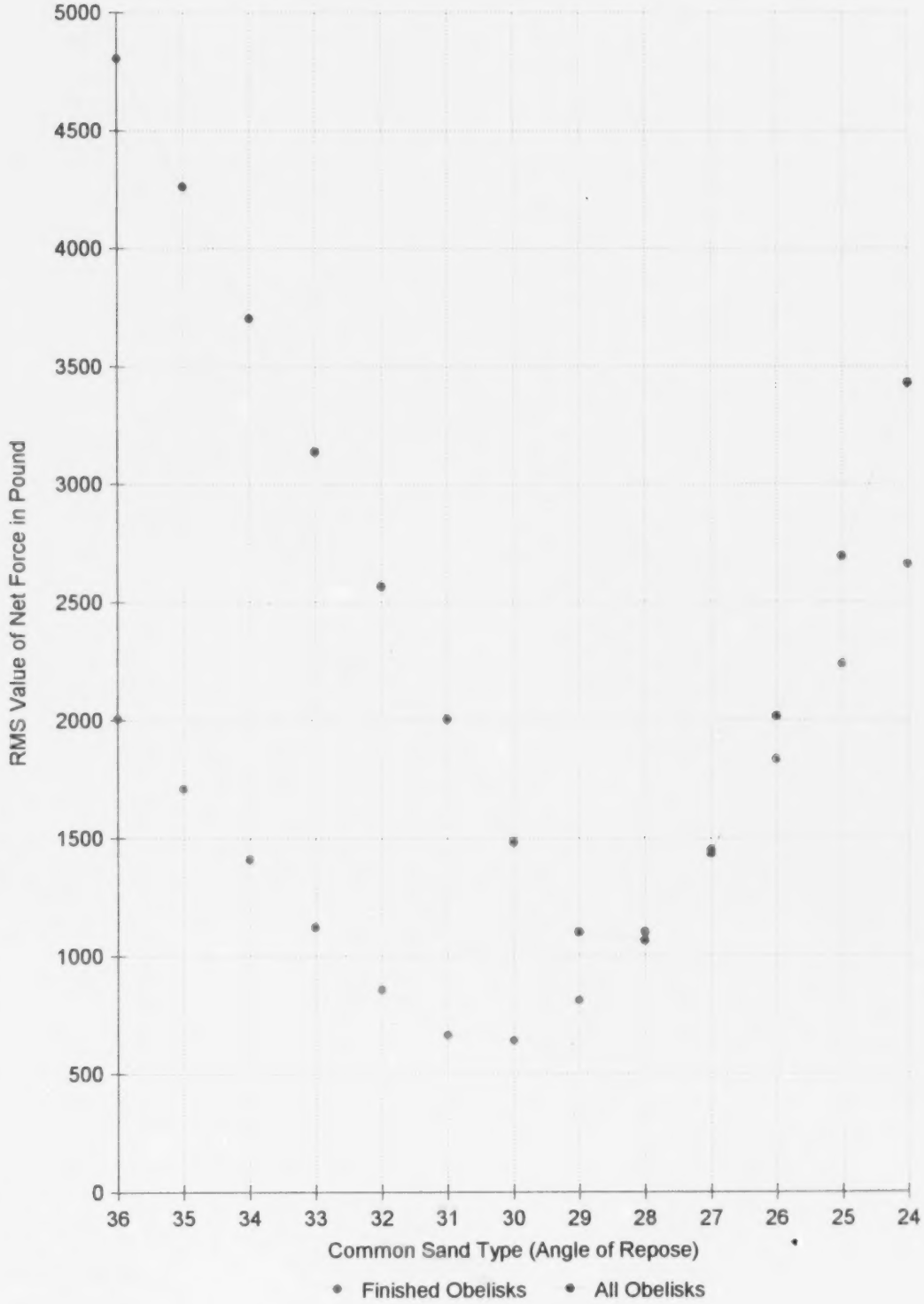

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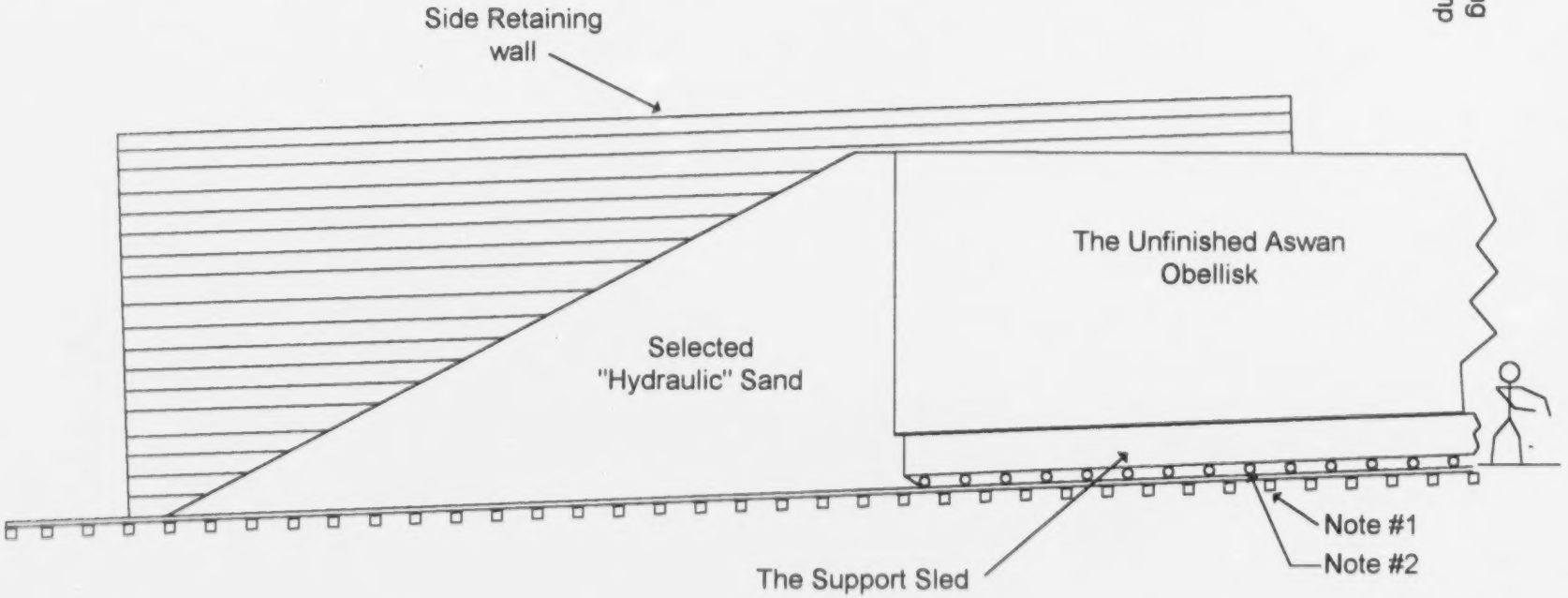
Figure #1
Cross Section of
Sand Engine for Moving
Aswan Obelisk Up Ramp

Scale
1/8" = 1'



Note #1 - Cross timbers beneath the planked "roadway" and above the wooden side walls are joined to vertical reinforcing timbers so that the "sand magazine" walls can contain the horizontal forces exerted by the pile of sand. The approach would be similar to placing structural ribs in a barge used on the Nile during this time period.

Note #2 - Supporting, wooden, rollers

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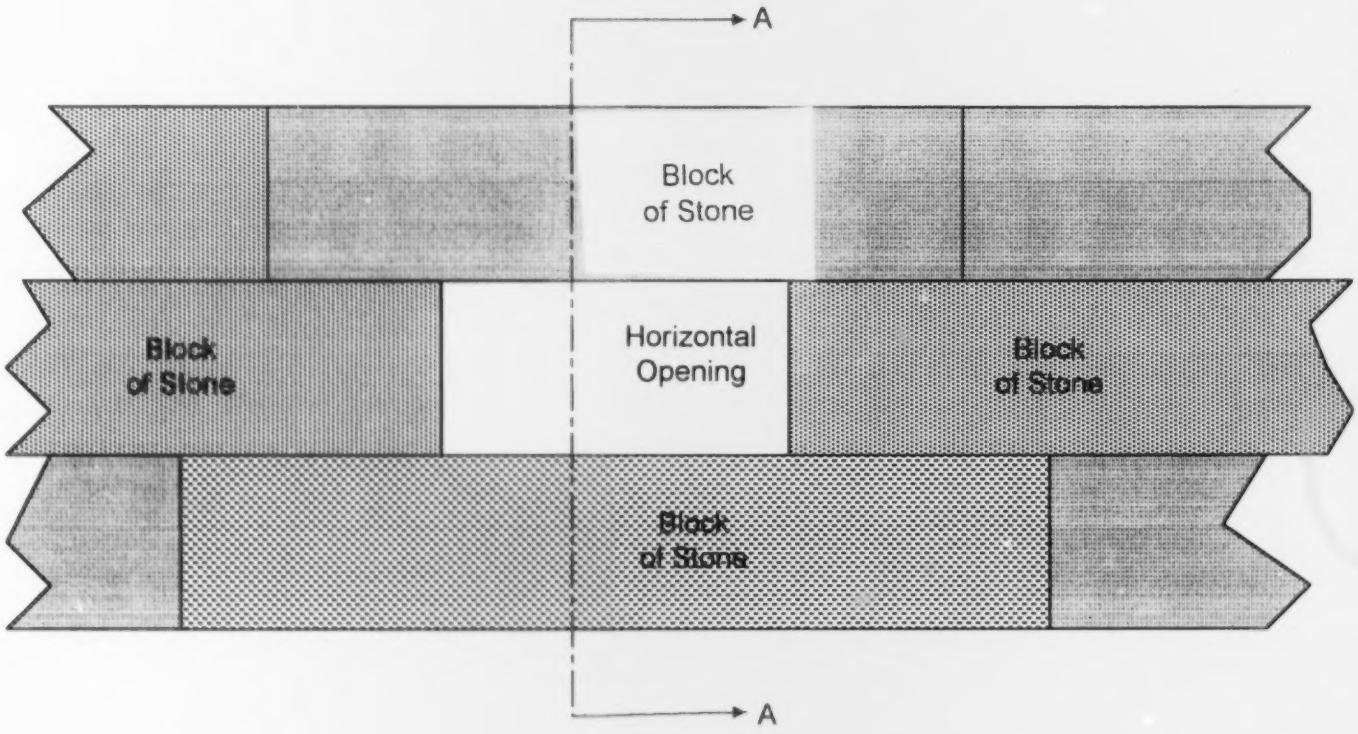
Figure #2
Section of Sand
Control Wall
Scale: 1"=2'



Section A-A

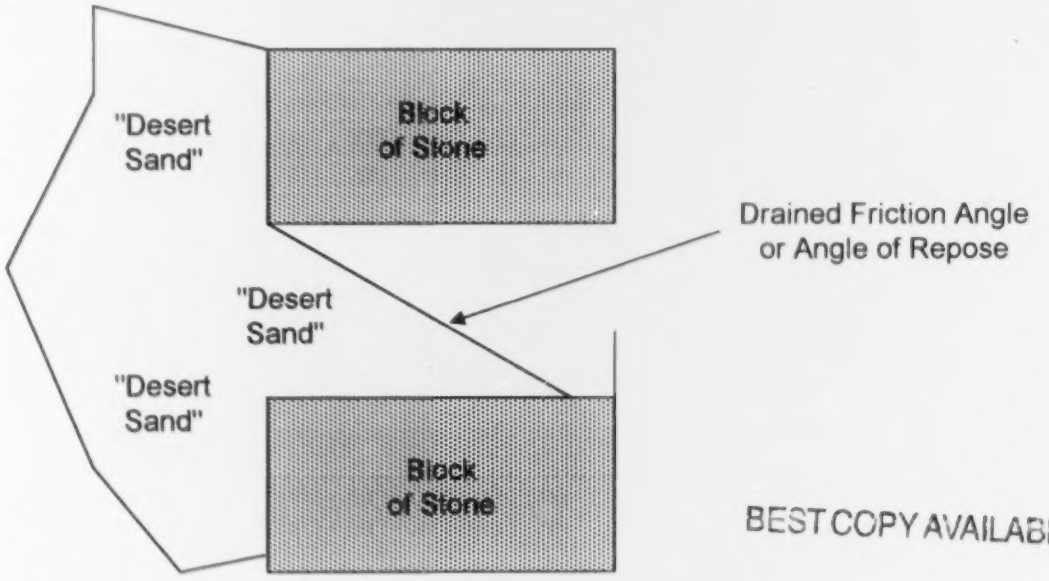


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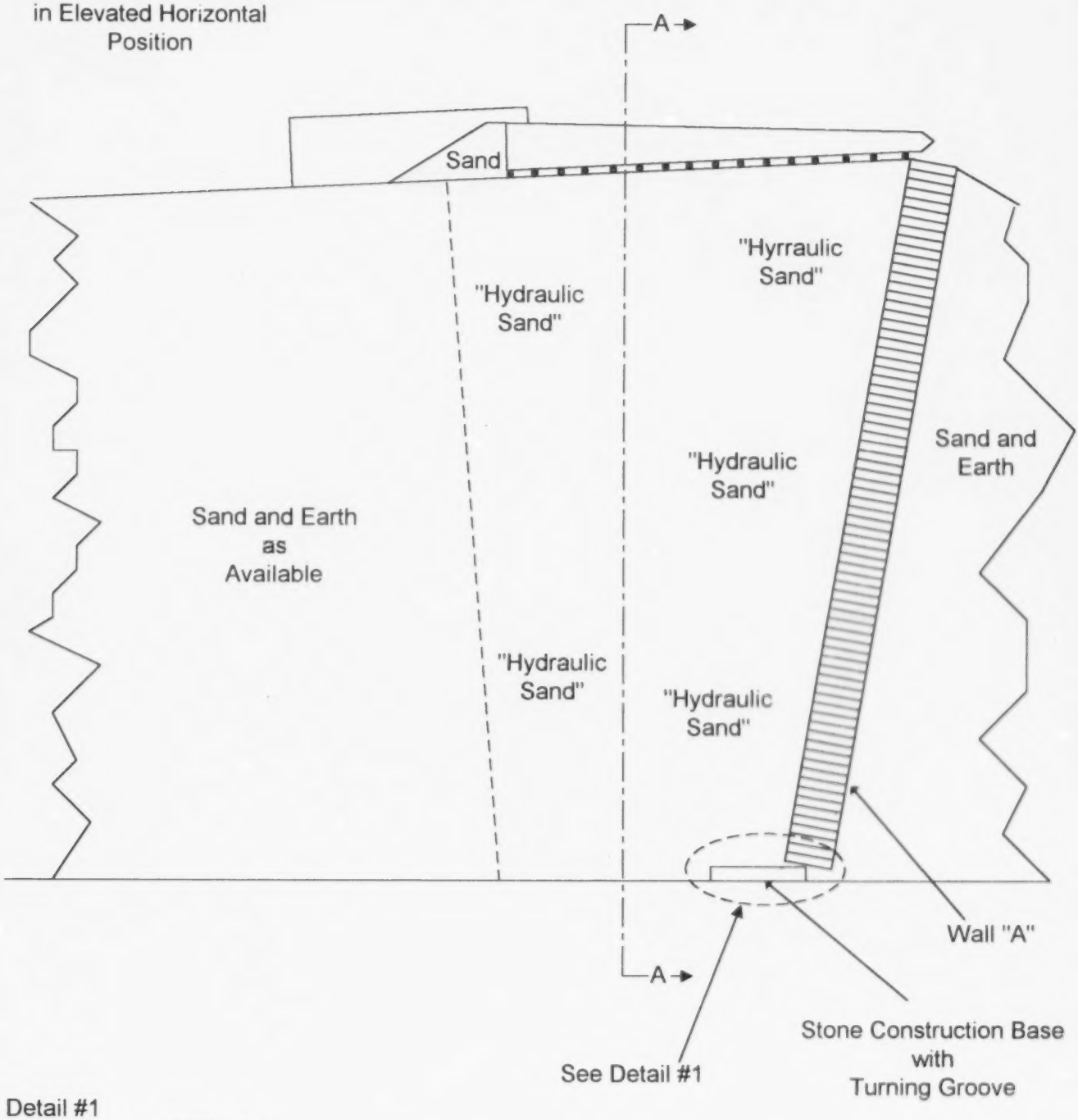
Figure #3

Cross Section of Obelisk in Elevated Horizontal Position



Detail #1 Enlarged

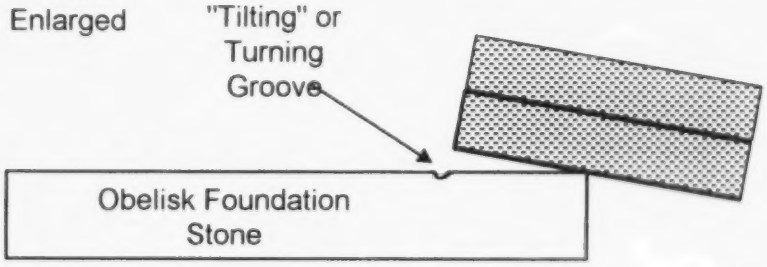


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Figure #4
Section A-A
of Figure 3

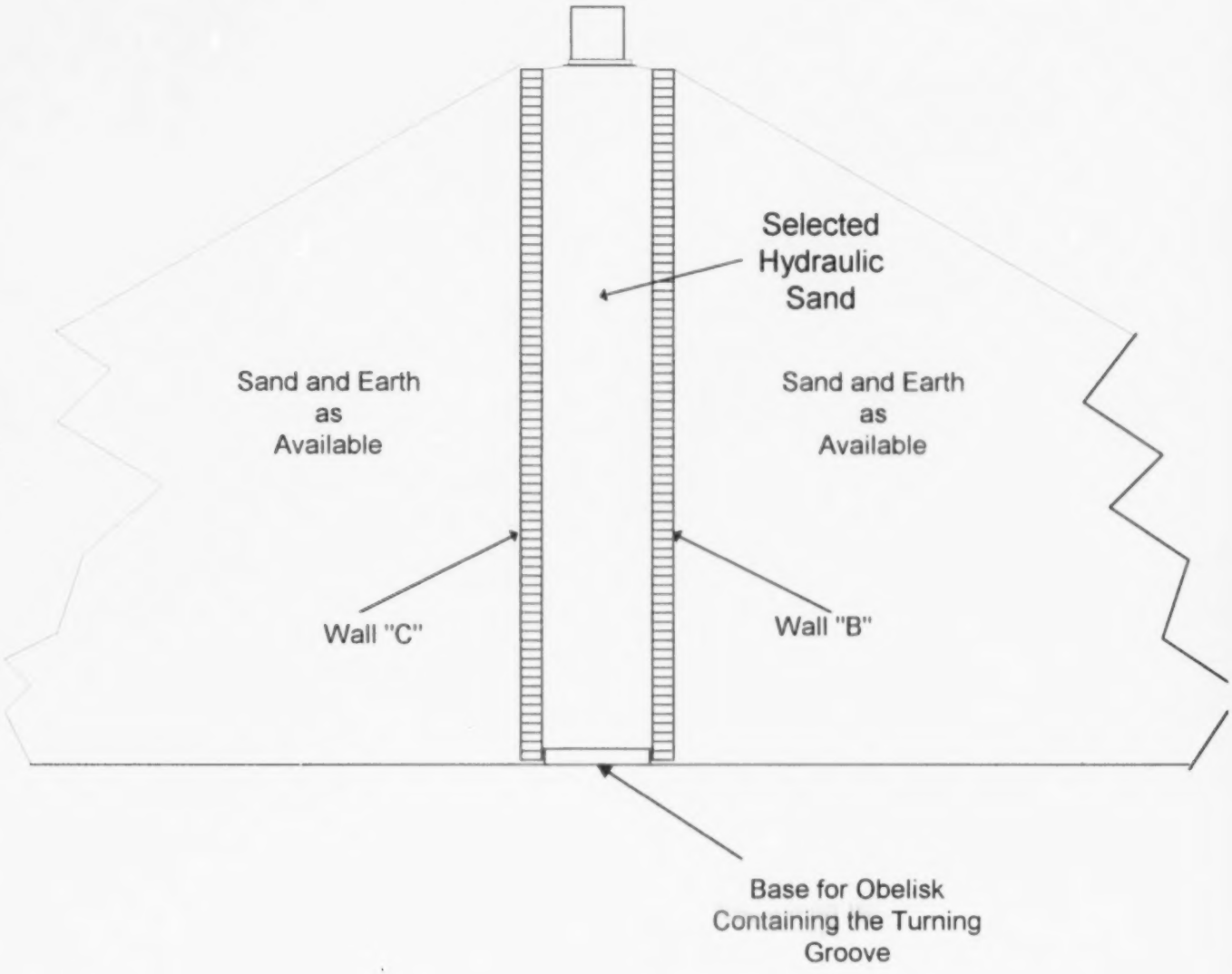

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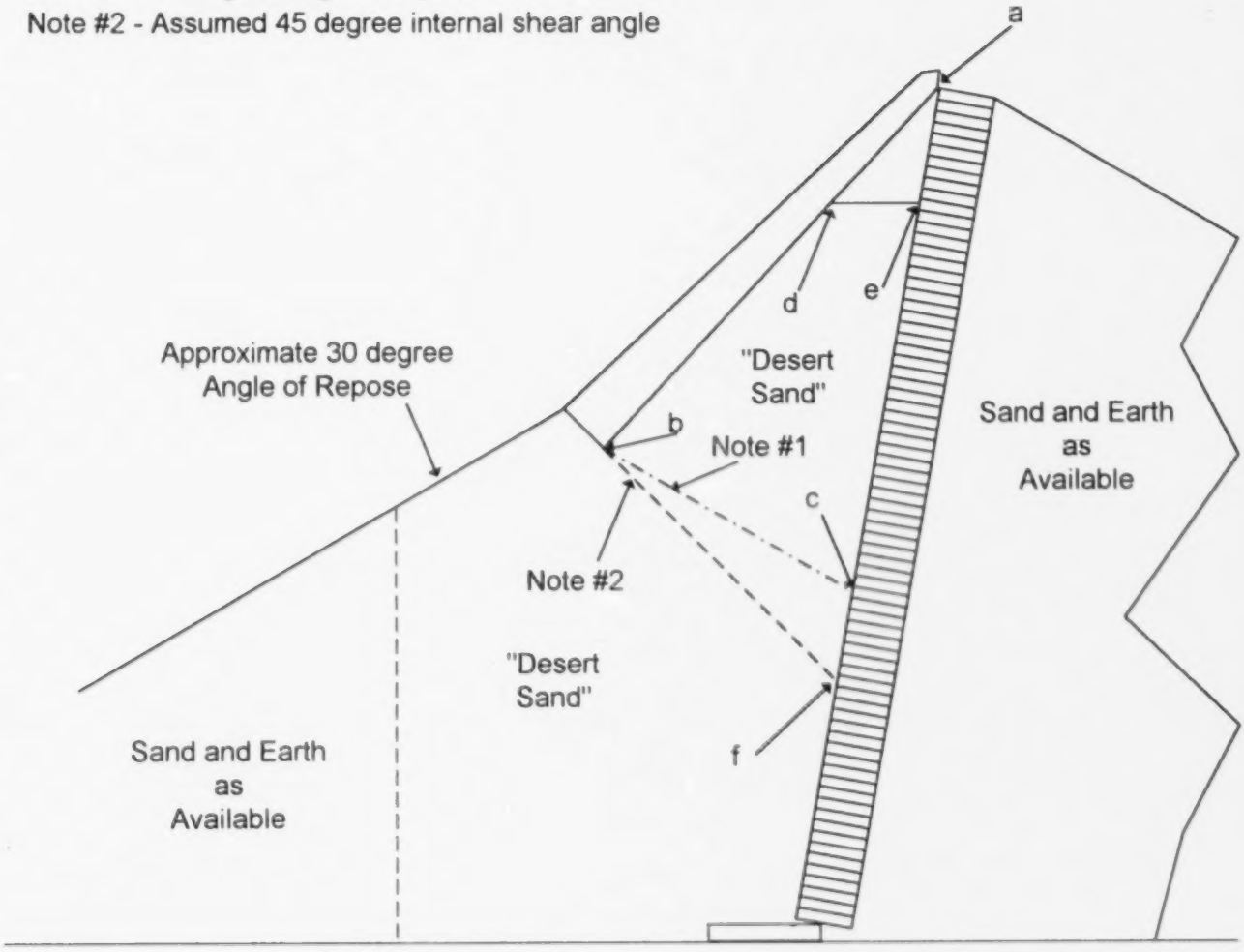
Figure #5
Cross Section of Partially
Rotated Obelisk

Note #1 - 30 degree angle of repose
Note #2 - Assumed 45 degree internal shear angle



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